12-11-2015

Improved Yield and Nitrogen Use Efficiency of Corn following Soybean in Irrigated Sandy Loams

Ahmed Attia
University of Nebraska - Lincoln, ahmed.attia@ag.tamu.edu

Charles A. Shapiro
University of Nebraska-Lincoln, cshapiro1@unl.edu

William Kranz
University of Nebraska - Lincoln, wkranz1@unl.edu

Mitiku Mamo
University of Nebraska-Lincoln, mmamo2@unl.edu

Michael Mainz
University of Nebraska - Lincoln

Published December 11, 2015

Improved Yield and Nitrogen Use Efficiency of Corn following Soybean in Irrigated Sandy Loams

Ahmed Attia*
Northeast Research and Extension Center
Haskell Agricultural Lab.
Univ. of Nebraska-Lincoln
57905 866 Rd.
Concord, NE 68728

currently at
Texas A&M AgriLife Research
Texas A&M Univ.
11708 Hwy. 70 S.
Vernon, TX 76384

Charles Shapiro
William Kranz
Mitiku Mamo
Michael Mainz
Northeast Research and Extension Center
Haskell Agricultural Lab.
Univ. of Nebraska-Lincoln
57905 866 Rd.
Concord, NE 68728

Crop rotation influences yield through its effects on nutrient and pest cycles, soil C, water availability, and soil physical and chemical properties. A cropping system study was conducted from 2004 to 2008 near Brunswick, NE, on sandy loam (Haplustolls) soils to evaluate improvements of irrigated corn (*Zea mays* L.) yield and N use efficiency (NUE) when following soybean [*Glycine max* (L.) Merr.] in 2 yr as corn following soybean (CS) or in 3 yr as first-year corn following soybean (C1) and second-year corn following soybean (C2) compared with continuous corn (CC). SPAD readings at V10 and R2 were approximately 3 to 4% greater in CS than CC, indicating more in-season N availability. Corn grain yield of CS (12.1 Mg ha^{-1}) was 20% greater than CC (10.1 Mg ha^{-1}), with 69 and 57% greater NUE and N recovery efficiency, respectively. At zero N applied, corn harvest index was 15% greater in CS with 37% increased plant N uptake at harvest compared with CC. In CS, fertilizer replacement value estimated soybean N credits of 66 and 49 kg N ha^{-1} based on grain yield and plant N uptake, respectively. The difference in N rates needed to produce maximum grain yield of CS vs. CC was estimated at 32 kg ha^{-1} soybean N credit. The average soybean N credit was 49, 41, and 26 kg N ha^{-1} for the corn in CS, C1, and C2, respectively. Both the 2- and 3-yr corn–soybean rotations on loamy sand soils improved corn yield and NUE.

Abbreviations: C1, first-year corn; C2, second-year corn; CC, continuous corn; CS, corn–soybean rotation; DNM, difference in nitrogen rates at maximum yield; FRV, fertilizer replacement value; HI, harvest index; NHI, nitrogen harvest index; NRE, nitrogen recovery efficiency; NUE, nitrogen use efficiency.

Corn is a major field crop grown in Nebraska, accounting for 12% of the total US corn production (National Agricultural Statistics Service, 2014). Of the 3.68 million ha planted to corn in Nebraska, about 45% are irrigated (National Agricultural Statistics Service, 2015). Soybean is another important field crop in Nebraska planted to 2.18 million ha, which is 7% of total US soybean production (National Agricultural Statistics Service, 2014). The irrigated soybean area is about 46% of the 2.18 million ha planted to soybean in Nebraska (National Agricultural Statistics Service, 2015). Continuous corn and a CS rotation are the predominant cropping systems of the state. In north-central Nebraska, corn under CS accounts for about 73% of the total area, while corn under CC accounts for 27% of the total area (B.S. Farmaha, personal communication, 2015). About 30% of the land in this area is either sand or sandy loam. In this region, excessive N application may occur when the N credit from the soil inorganic-N content or a previously grown legume crop is not adequately considered. Thus, defining efficient N management for these cropping systems in Nebraska is needed to produce more yield while minimizing negative environmental impacts.

Soil Sci. Soc. Am. J. 79:1693–1703
doi:10.2136/sssaj2015.05.0200
Open Access.
Received 24 May 2015.
Accepted 17 Aug. 2015.
*Corresponding author (ahmed.attia@ag.tamu.edu).

Sandy soils in Nebraska are characterized by low cation exchange capacity and soil organic matter (Soil Conservation Service, 1983), hence they are more dependent on the application of N for high corn yields. While N is universally accepted as an important component to high corn yield and economic return, keeping inorganic N in the root zone and available when the crop needs it is a challenge in coarse-textured soils. Soil parameters such as inorganic-N content, pH, organic matter content, soil water content, temperature, and soil structure and texture are different in coarse-textured soils than in silts and clay loams. Coarse-textured soils have been reported to have greater mineralization rates of soil organic N than fine-textured soils on an organic matter percentage basis (Hassink, 1994). Coarse-textured soils are also characterized by rapid permeability and low water holding capacity, which affect the residual soil N concentration. This, combined with the timing of precipitation and irrigation, will affect how much NO_3 is available for the subsequent crop on sandy soils.

Corn–soybean rotations can enhance yield productivity through improved soil physical, chemical, and biological conditions (Raimbault and Vyn, 1991; Jawson et al., 1993; Katupitiya et al., 1997; Boyer et al., 2015). Rotation of corn to soybean produced greater grain yield of both crops on a silty clay loam soil (Varvel, 1994; West et al., 1996), with less input costs (Foltz et al., 1995), and less N compared with CC (Varvel and Wilhelm, 2003). Corn yield was increased by 21% and soybean yield by 9% when grown in rotation compared with monoculture on a silty clay loam (Wilhelm and Wortmann, 2004). First-year corn showed grain yield increases of 79 to 100 kg ha^{-1} yr^{-1} when planted in 5-yr rotations of corn, soybean, oat (*Avena sativa* L.), and alfalfa (*Medicago sativa* L.) with less N input on a Rozetta silt loam soil, whereas the 2-yr rotation was not sufficient to improve grain yields (Stanger and Lauer, 2008). Continuous corn required more N with a yield penalty of 1.36 Mg ha^{-1} at the agronomic optimum N rate compared with CS over a 6-yr period on a Flanagan silt loam soil (a mesic Aquic Argiudoll) in east-central Illinois (Gentry et al., 2013).

Previous research conducted on irrigated loamy sand or silty loam soils did not find a soybean N contribution to the following corn (Hesterman et al., 1986; Bundy et al., 1993; Ennin and Clegg, 2001) because of NO_3^-–N lost through leaching before it could be recovered by the corn. Angle (1990) documented the greatest mineralized soil-N concentrations following soybean at the surface of a coarse loamy soil in the fall. This soil N moved to the 0.9- to 1.2-m soil depth in the spring, indicating leaching loss. Nitrogen recovery by the succeeding corn crop is based on the amount of mineralized N and the N leaching potential.

Crop rotation improves N use efficiency (NUE) by reducing requirements for external inputs of N fertilizer. Several reports have documented higher NUE for CS than CC (Huang et al., 1996; Huggins and Pan, 2003; Pikul et al., 2005; Wortmann et al., 2011). Nitrogen recovery efficiency can be also improved by the application of economically optimum N rates that consider residual soil N and N credits from a previous legume crop. Lord and Mitchell (1998) reported an the N recovery efficiency (NRE) for corn on sandy soils of 0.52 kg N kg^{-1} applied N below the economically optimum N rate, which declined to 0.05 kg N kg^{-1} applied N above the economically optimum N rate. Wortmann et al. (2011) reported that a CS rotation increased the NRE by 10% at the economically optimal N rate compared with CC during a multiple site-year study on silt loam and loamy sand soils. Others have found that an increased N rate decreased internal and physiological N efficiency for CC on a Knoke loam soil (a cumulic Vertic Endoaquoll) (Sindelar et al., 2015).

In addition to increasing grain yield and NUE, research has found that planting corn into soybean residue achieves yield increases with less N than when soybean is planted into corn residue. Corn in CC responded to 30 to 65 kg more N ha^{-1} with lower grain yield productivity per unit of N applied compared with CS (Ding et al., 1998; Varvel and Wilhelm, 2003). Others have reported 10 to 32% corn grain yield increases with lower N inputs when corn followed a legume compared with CC (Peterson and Varvel, 1989; Crookston et al., 1991; Riedell et al., 1998). Previous research has reported soybean N credits to the following corn of 30 kg N ha^{-1} (Ding et al., 1998), 65 kg N ha^{-1} (Varvel and Wilhelm, 2003), and 75 kg N ha^{-1} (Blevins et al., 1990). In contrast, others have found that soybean can be an effective N sink; based on the change in soil NO_3^-–N, NO_3^-–N concentrations were reduced 36 kg N ha^{-1} (Vanotti and Bundy, 1995) and 48 kg N ha^{-1} (Ennin and Clegg, 2001).

Nitrogen credit from the preceding legume is associated with the potential for biological N_2 fixation by legume–*Rhizobium* symbiosis, which is probably affected by inherent soil chemical and physical properties and seasonal growing conditions. Research has identified biological N_2 fixation as responsible for the greatest contribution to the beneficial effects of rotation (Peoples and Herridge, 1990; Mohammed and Clegg, 1993; Salvagiotti et al., 2009). Nonetheless, other factors may reduce N_2 fixation in the nodules, such as soil water content (Purcell et al., 2004), soil pH (Parker and Harris, 1977), and soil temperature (Soares Novo et al., 1999), when no other abiotic stress exists. In addition, the negative effect of corn residue under CC on soil N immobilization and mineralization is a main contributor to the soybean N credit following corn (Trinsoutrot et al., 2000; Gentry et al., 2001).

Improving N management for corn could be achieved by determining plant N status during the growing season. Previous research showed that SPAD readings taken at the V7 or V8 stage of corn could determine N deficiency, with a high likelihood that supplemental N will correct the deficiency (Varvel et al., 1997a). Piekielek et al. (1995) reported that SPAD readings at late milk to mid-dent stages of corn accurately differentiated N deficiency from N sufficiency treatments and were correlated to relative grain yield. While SPAD meter readings do not distinguish excess N, the corn stalk NO_3^-–N test was found to be effective in determining N excess and improving the N recommendation for the following year (Fox et al., 2001; Forrestal et al., 2012). Gaps remain in knowledge about how corn yield and N uptake increase when grown in a CS rotation compared with

CC on the irrigated sandy loam soils of north-central Nebraska. The objectives of this study were (i) to determine the effects of 2- or 3-yr CS rotations (soybean–corn–corn, corn–soybean–corn, and corn–corn–soybean) compared with CC on N indicators such as SPAD readings and stalk NO_3^-–N and on corn yield, N uptake, and measures of NUE and NRE on sandy loam soils, and (ii) to calculate the average soybean N credit to corn in 2- to 3-yr rotations. A related goal was to evaluate the effects of six N rates on soybean yield grown as part of the rotations.

MATERIALS AND METHODS

Site Description and Cultural Practices

A 5-yr rotation study was initiated in 2004 on a farmer's field near Brunswick, NE (42°20′ N, 79°55′ W) on a mixture of a Thurman loamy sand (a sandy, mixed, mesic Urdorthentic Haplustoll) and a Boelus loamy sand (sandy over loam, mixed, superactive, mesic Udic Haplustoll). The field had been in a CS rotation for >10 yr, with soybean as the preceding crop in 2003. The 3-yr rotation was established in 2004 and 2005, and then data were collected in 2006 to 2008. The establishment years (2004 and 2005) were needed to get all phases of the rotation being grown in the same year. Average air and soil temperature, precipitation, and irrigation during the summer seasons of 2006 to 2008 are shown in Table 1. The field was irrigated using a center-pivot sprinkler irrigation system. Irrigation was scheduled by a professional certified crop consultant who scheduled irrigation based on soil water content (maintaining >50% available water) on a weekly basis. Groundwater with a Na adsorption ratio of 0.3 and irrigation water NO_3^-–N concentration of 20 mg L^{-1} was used as the source of irrigation; N applied as irrigation water NO_3^-–N was 26, 81, and 60 kg ha^{-1} in 2006, 2007, and 2008, respectively.

For each replicate, four core soil samples were taken from the 0- to 0.20-, 0.20- to 0.58-, and 0.58- to 1.22-m soil depths in April 2004 and then composited to determine soil pH and associated chemical properties (Table 2). Based on soil analysis results, 1360 kg ha^{-1} pelleted lime was broadcast applied on 15 Apr. 2005 to increase the soil pH.

Typical cultural practices used by local producers were used in this study. Corn hybrids Pioneer 34A18 LL/CRV, Dekalb DKC 60-18 RR2/YGPL, and NuTech 1×112 HTX were planted on 13 May 2006, 2007, and 2008, respectively, under a no-till system with a John Deere 6420 six-row planter, with plant populations ranging from 75,695 to 80,567 plants ha^{-1}. A 3-m-wide drop spreader (Barber Engineering Co.) was used to broadcast 112 kg K ha^{-1} as potassium magnesium sulfate (0–0–21–21–11 N–P–K–S–Mg) and 78 kg P ha^{-1} as monoammonium phosphate (11–23–0 N–P–K). Gly Star Plus [glyphosate, *N*-(phosponomethyl)glycine] herbicide was applied twice each year in late May and late June at a rate of 1.36 kg a.i. ha^{-1}, and Dual II magnum (S-metolachlor, 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(1*S*)-2-methoxy-1-methylethyl]acetamide) was applied in early May each season at a rate of 1.28 kg a.i. ha^{-1} for weed control.

Asgrow 2703 RR soybean was planted on 12 May 2006 and 14 May 2007, and Pioneer 93M11 RR was planted in 13 May 2008, with an average plant population of 435,000 plants ha^{-1}. Weeds were controlled by post-emergence herbicide application of Gly Star Plus twice per season at a rate of 1.36 kg a.i. ha^{-1} and Dual II magnum once per season at a rate of 1.28 kg a.i. ha^{-1}. In 2006 and 2008, there was an aerial application of chlorpyrifos [*O*,*O*-diethyl-*O*-(3,5,6-trichloro-2-pyridinyl)phosphorothioate] in mid-August at a rate of 1.13 kg a.i. ha^{-1} for aphid control.

Experimental Design and Data Collection

The experimental design was split plot in a randomized complete block design with four replicates. Seven rotations were assigned to whole plots that included (i) CC, (ii) CS, (iii) soybean–corn, (iv) continuous soybean, (v) soybean–corn–corn,

Table 1. Average monthly temperature, soil temperature, precipitation (*P*), and irrigation (*I*) during the summer seasons of 2006 to 2008 at Brunswick, NE.

	2006				2007				2008			
Month	Avg. temp.	Soil temp.	*P*	*I*	Avg. temp.	Soil temp.	*P*	*I*	Avg. temp.	Soil temp.	*P*	*I*
	— °C —		— mm —		— °C —		— mm —		— °C —		— mm —	
May	17†	18	13‡	17	17	18	159	24	13	14	198	26
June	22	23	93	76	21	20	73	53	20	23	70	53
July	25	28	13	46	24	27	30	186	23	27	83	133
Aug.	22	25	60	0	23	25	109	122	22	26	59	107
Sept.	15	17	117	0	17	19	79	32	17	19	50	0

† Monthly temperature and soil temperature values were obtained from the Concord weather station, Concord, NE.

‡ Precipitation and irrigation water were recorded by rain gauges installed in the field.

Table 2. Analysis of soil samples collected before initiation of the field study at Brunswick, NE, in 2004.

Sample depth	pH	Bray 1-P†	Extractable K†	NO_3^--N	SOM‡	Texture
cm		mg kg^{-1}			g kg^{-1}	
0–20	5.6	45.8	181	3.0	9.3	loam to sandy loam
20–60	5.1	19.3	112	3.8	7.8	sandy loam
60–120	5.7	5.7	117	3.6	4.8	loam to sandy loam

† Bray 1-P and extractable K values are classified as very high according to the general guide for crop nutrient and limestone recommendations in Iowa.

‡ Soil organic matter.

(vi) corn–soybean–corn, and (vii) corn–corn–soybean. These rotations provided four corn rotation treatments and three soybean rotation treatments each year. Corn rotation treatments were continuous corn (CC), corn following soybean (CS), first-year corn following soybean (C1), and second-year corn following soybean (C2), while soybean rotation treatments were continuous soybean (SS), soybean following corn (SC), and second-year soybean following corn (S2). Whole plots i and iv provided CC and SS treatments, respectively. Whole plots ii and iii provided CS and SC treatments. Whole plots v, vi, and viii provided C1, C2, and S2 treatments.

Whole plots were 9.1 m wide (12 0.76-m rows) by 63 m long, and subplots were 9.1 m wide (12 0.76-m rows) by 9 m long. Subplot treatments were six N rates (0, 56, 112, 168, 224, and 280 kg ha^{-1} for corn and 0, 20, 40, 60, 80, and 100 kg ha^{-1} for soybean). Each year, the 12-row-wide plot was split in half, and six rows were designated as "bulk" and the other six were treatments with the randomized N rates. The bulk area was fertilized with a uniform N rate that was slightly below the University of Nebraska–Lincoln recommendation (Shapiro et al., 2008) so excess N did not carry over to the next year. The six N rates were randomized each year, and they were applied on the previous year's bulk strips. The entire experiment had the same split for bulk vs. N rate. In other words, one year the northern six rows were the bulk area, the next year the southern six rows. This pattern was continued for the entire experiment. Therefore, each year N was applied to part of the plot that had a uniform N application in the previous year, so N rate effects were not additive over time. Nitrogen rates were applied as NH_4NO_3 (330 g N kg^{-1}) three times during the season that included 40% spread pre-emergence, 30% spread at V6 (Ritchie et al., 1993), and the remaining 30% spread at V11. The NH_4NO_3 was weighed out for each plot and hand applied. On the bulk strips, N was applied with a coulter-and-knife applicator at pre-emergence and V11 as urea–NH_4NO_3 (320 g N kg^{-1}). Plant population counts were collected on 3 July 2006 and 2008 and 11 July 2007.

Minolta SPAD 510 (Spectrum Technologies Inc.) readings were recorded at the V10 and R2 (blister) stages in 2006 to 2008 using the method described by Shapiro et al. (2006). Each SPAD value was an average of 30 readings per experimental unit. The relative index produced by the SPAD meter is used as a surrogate for relative amounts of chlorophyll in the corn leaves. An end-of-season basal stalk NO_3^-–N test to determine the NO_3^-–N content in the stalks (mg kg^{-1}) was conducted only in 2007 and 2008 at physiological maturity by sampling 10 plants (Binford et al., 1990). The plants were taken from the second row in 2007 and from the second and fifth rows in 2008. To determine whole-plant dry matter, six plants were cut at ground level outside the harvest area from the second and fifth rows after physiological maturity; the ears were separated, air dried, and weighed, then shelled in 2006 to 2008. Stalks and leaves (stover) were weighed and then chopped in a Vermeer BC600XL brush chipper. Stover subsamples were collected, weighed, and oven dried in a forced-air drier to determine water and N contents (Bremner, 1996). Nitrate in the stalks, stover N concentration, and grain N concentration were determined at Ward Laboratory (Kearney, NE). Total N uptake was determined by combining stover and grain N uptake.

Two rows of corn or soybean were machine harvested with a plot combine equipped with a weighing system in all years except 2007, when three rows of corn were harvested. A subsample was collected and water content measured; the yield of corn or soybean was adjusted to 155 or 130 g kg^{-1} water content, respectively. Harvest index and N harvest index were calculated by dividing the grain yield by the biomass yield and the grain N content by the total aboveground N content, respectively. Two N efficiency parameters (Cassman et al., 2002) were calculated each year, NUE (kg increased grain yield kg^{-1} N) and NRE (kg increased plant N uptake kg^{-1} N):

$$\mathrm{NUE}=\frac{\text{grain yield}_{\text{treatment N}}-\text{grain yield}_{0\ \text{N}}}{\text{N applied}_{\text{treatment N}}+\text{irrigation } NO_3\text{–N}}\quad[1]$$

$$\mathrm{NRE}=\frac{\text{N uptake}_{\text{treatment N}}-\text{N uptake}_{0\ \text{N}}}{\text{N applied}_{\text{treatment N}}+\text{irrigation } NO_3\text{–N}}\quad[2]$$

After harvest at the end of the study, four soil cores per rotation whole plot were collected in spring 2009 from the 0- to 0.15-m soil depth. Soil samples were air dried, composited, and analyzed for soil texture, pH, and soil C and NO_3 content.

Statistical Analysis

Analysis of variance was performed on the corn or soybean phase of the rotations using PROC GLIMMIX (SAS Version 9.3, SAS Institute). Rotation, N rate, and their interaction were considered as fixed effects. Year, replicate, and their interactions with rotation were considered as random effects. Considering year as a random source of error allows the conclusions on treatment effects to be broadened across a range of environments (Carmer et al., 1989). The stalk NO_3^-–N test was not measured in 2006, thus the combined ANOVA was conducted across 2007 and 2008. Otherwise, the combined ANOVA was conducted across 2006 to 2008 for the remaining variables. Treatment means were separated by the protected LSD at the $P \leq 0.05$ significance level.

A modified Cate–Nelson graph (Cate and Nelson, 1971) was used to determine the critical SPAD reading level at which corn might not respond to N application. In this procedure, the relative grain yield (GY/GY_{max}) calculated as a ratio of yield to maximum yield each year within each cropping system was plotted against relative SPAD reading calculated as a ratio of SPAD reading to maximum SPAD reading each year within each cropping system, and then horizontal and vertical lines were drawn. The horizontal line of relative grain yield was set at 0.95, whereas the vertical line was set to minimize the number of points in the upper left quadrant and the lower right quadrants. Outliers in the upper left quadrant are points for which the test underestimates N status (incorrectly suggesting that more N is needed), whereas outliers in the lower right quadrant are points for which the test overestimates N status (indicates more N might have increased yields). Pearson's correlation of SPAD readings at V10 and R2 and stalk NO_3^-–N with grain yield was performed using PROC CORR in SAS. The response of variables to a rotation × N rate interaction was analyzed by linear, second-order polynomial, and linear plateau models utilizing the *drc* statistical addition package (Ritz and Strebig, 2010) in R Version 2.1.0 (www.r-project.org).

RESULTS AND DISCUSSION

Initial soil analysis indicated lower than recommended pH, adequate P and K, and low soil organic matter content (Table 2). High P concentration in the initial soil analysis was probably due to sampling after farmer-applied fertilizer. Analysis in spring 2009 showed that the pH had increased to acceptable levels (6.45), whereas P decreased to critical levels (16.4 mg kg^{-1}) across rotations. The NO_3^-–N concentrations (2.1 mg kg^{-1}) were all low in each year and were typical for similar soils, contributing minimal N to the succeeding crop. Only a trend for higher soil organic matter was observed for CC (11.2 g kg^{-1}) compared with SS (9.9 g kg^{-1}), with values for CS and C2 in between. This could be attributed to less residue returned to the soil by soybean in SS or CS than by corn in CC during the life of the rotation. Varvel (1994) reported twice the residue returned to the soil by corn compared with soybean.

Nitrogen Indicators

All in-season N indicators supported the conclusion that more soil N was available to corn when soybean was in the rotation (Table 3). The first in-season indicator measured was the greenness by the SPAD readings taken at the V10 and R2 growth stages. Rotation and N rate significantly affected SPAD readings at R2, but the interaction was not significant. An increase of 1 to 2 SPAD readings for CS and C1 compared with CC suggests that more N got into the plants when corn was rotated with soybean in the CS and C1 rotations.

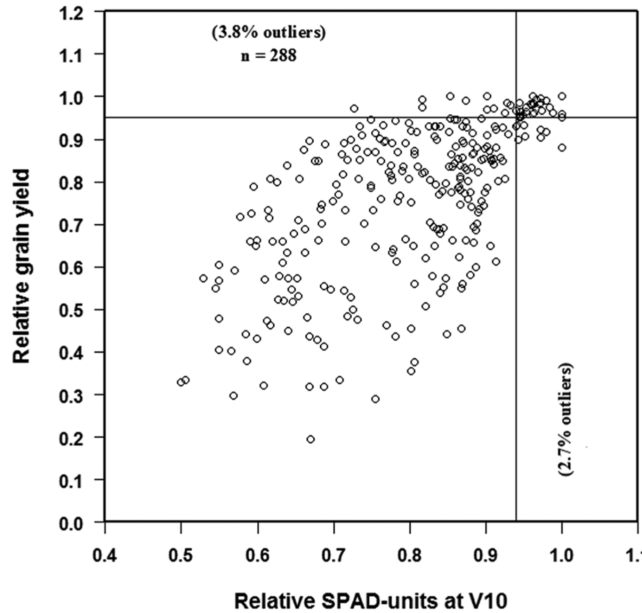

Fig. 1. A modified Cate–Nelson graphic analysis of corn relative grain yield relationship with SPAD readings recorded at the V10 stage. Relative grain yield was calculated as grain yield relative to maximum yield within each cropping system. Rotations included continuous corn, corn–soybean, first-year corn following soybean, and second-year corn following soybean.

A modified Cate–Nelson graphic analysis (Cate and Nelson, 1971) was used to determine the critical SPAD readings at the V10 and R2 growth stages, where greater readings are considered non-responsive to N application. For V10, the relative SPAD readings that minimized outliers was 0.94 (Fig. 1). Only 3.8% of the 288 points were outliers in the upper left quadrant

Table 3. SPAD readings at V10 and R2, corn stalk NO_3^-–N, soybean seed yield, corn stover and grain yields, and corn harvest index (HI) as affected by rotation (R), N rate (N), and their interaction during 2006 to 2008.

Rotation	df†	SPAD at V10	SPAD at R2	Stalk NO_3^-–N‡	Soybean seed yield§	Corn yield		HI
						Stover	Grain	
				mg kg^{-1}	Mg ha^{-1}			
CC¶		43.8	50.3 b#	1508 b	4.29	8.1 b	10.1 c	0.49 b
CS		44.8	52.3 a	2323 a	4.33	9.0 a	12.1 a	0.52 a
C1		44.9	52.4 a	2155 a	4.30	8.8 a	11.7 a	0.52 a
C2		44.4	50.8 b	1468 b	–	8.5 ab	11.0 b	0.50 ab
Source of variation					ANOVA ($P > F$)			
R	3	0.073	0.001	0.009	0.970	0.018	<0.0001	0.020
N	5	<0.0001	<0.0001	<0.0001	0.667	<0.0001	<0.0001	<0.0001
N linear	1	<0.0001	<0.0001	<0.0001	0.772	<0.0001	<0.0001	<0.0001
N quadratic	1	<0.0001	<0.0001	<0.0001	0.194	<0.0001	<0.0001	0.001
R × N	15	0.971	0.250	0.286	0.118	0.425	0.089	0.192
CV, %		3.9	5.2	37.5	5.4	14.4	9.4	6.9

† Degrees of freedom for soybean are 2, 5, and 10 for R, N, and R × N, respectively.

‡ Analysis and rotation means for stalk NO_3^-–N test were conducted for 2007 and 2008 only.

§ Soybean seed yield for rotations continuous soybean (SS), soybean–corn (SC), and second-year soybean (S2), respectively.

¶ CC, continuous corn; CS, corn in a corn–soybean rotation; C1, first-year corn; C2, second-year corn.

Least significant difference at the 95% confidence level by GLIMMIX-SAS procedure; means in each column followed by the same letter are not significantly different.

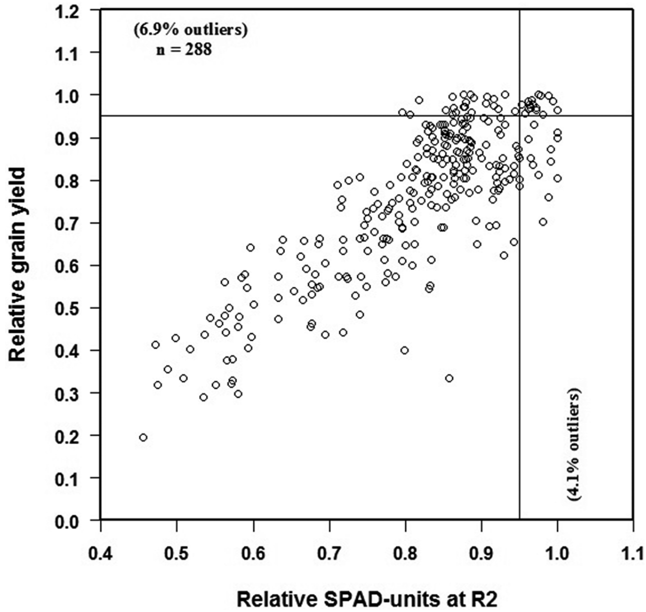

Fig. 2. A modified Cate–Nelson graphic analysis of corn relative grain yield relationship with SPAD readings recorded at R2 stage. Relative grain yield was calculated as grain yield relative to maximum yield within each cropping system. Rotations included continuous corn, corn–soybean, first-year corn following soybean, and second-year corn following soybean.

and only 2.7% were outliers in the lower right quadrant. At the R2 growth stage, the results indicated a that critical SPAD reading of 0.95 minimized outliers (Fig. 2). The percentage of outliers was limited to 6.9% in the upper left quadrant and 4.1% in the lower right quadrant. Therefore, we conclude that the critical level of 0.95 relative SPAD reading in the present study on sand is consistent with that developed on silt loam soils as a threshold for N application (Shapiro et al., 2006).

Rotation and N rate significantly affected stalk NO_3^-–N concentration in 2007 and 2008 (Table 3). Corn–soybean and C1 had significantly greater stalk NO_3^-–N concentrations than CC and C2 (Table 3). Although there was a significant quadratic response to N in the ANOVA for stalk NO_3^-–N, the linear model with a forced intercept to zero fitted the data better ($P <$ 0.0001 and higher r^2) and so is presented as such. Stalk NO_3^-–N concentration increased linearly as the N rate increased for all rotations, with the greatest rate of stalk NO_3^-–N increase occurring for CS (Fig. 3, slope = 17.532 mg kg^{-1} stalk NO_3 kg^{-1} N). Using the interpretation of Blackmer and Mallarino (1996), the applied N rate is excessive when the stalk NO_3^-–N is >2000 mg kg^{-1}. Based on this interpretation and using the linear relationship between stalk NO_3^-–N and N rate, the predicted N rate at which the stalk NO_3^-–N concentration would be 2000 mg kg^{-1} was 165 kg N ha^{-1} for CC and 180 kg N ha^{-1} for C2, whereas it was about 135 kg N ha^{-1} for C1 and 115 kg N ha^{-1} for CS (Fig. 3). Similar to these results, the significant rotation × N rate interaction on stalk NO_3^-–N concentration reported by Varvel et al. (1997b) showed that corn reached the threshold concentration of 2000 mg kg^{-1} at 155 kg N ha^{-1} in CC and 110 kg N ha^{-1} in CS over 3 yr in silt loam soils (Pachic Haplustolls).

Yield Traits and Harvest Index

Rotation, N rate, and their interaction did not significantly influence soybean seed yield (Table 3). Treatment effects on seed yield were consistent across years, averaging 4.31 Mg ha^{-1}. When no fertilizer N was applied, seed yield was the greatest in SC followed by SS and S2. Because there was N supply derived from mineralization, N_2 fixation, and irrigation water NO_3^-–N, crop N needs were met without the need for fertilizer N. The lack of a significant soybean response to N agrees with previous re-

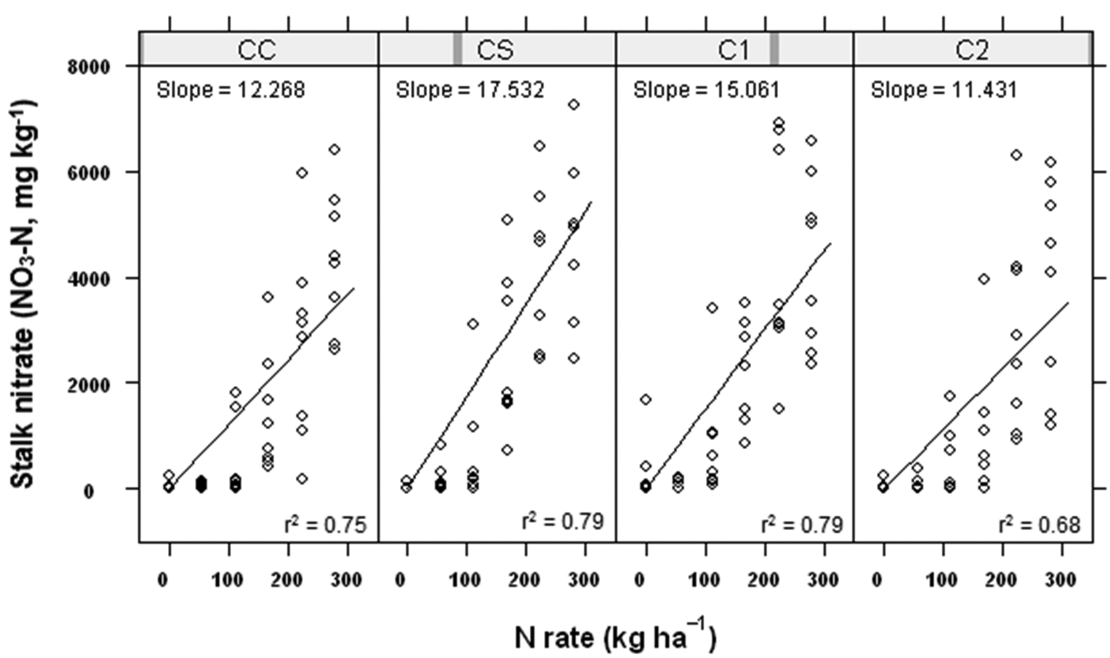

Fig. 3. Relationship between corn stalk NO_3^-–N and applied fertilizer N rate for rotations in 2007 and 2008. Analysis was conducted on the corn phase of continuous corn (CC), corn–soybean or soybean–corn (CS), and soybean–corn–corn, corn–soybean–corn, or corn–corn–soybean rotations that provided first-year corn (C1) and second-year corn (C2).

search findings (Varvel and Peterson, 1992; Schmitt et al., 2001; Halvorson and Reule, 2006) where N derived from indigenous sources such as net soil N mineralization was enough to meet the crop N requirements.

Rotation and N rate significantly affected corn stover and grain yields (Table 3). For both stover and grain, CC was the lowest yielding rotation followed by C2 and C1/CS. We observed that corn had 11% greater stover and 20% greater grain yield in CS than in CC. Although not always significant, the trend was for CS to have greater productivity than either C1 or C2 (Table 3). The interactions between rotation and N rate for grain yield are shown in Fig. 4a, along with the fitted quadratic regression for each rotation. The C2 rotation did not reach maximum yield with the N rates used in this study. The impact of these relationships on a soybean N credit are discussed below. Greater corn yield in CS vs. CC could be attributed to factors related to the relatively high C/N ratio residue deposited in larger quantities under CC than CS. Research conducted to identify the reasons for the CC yield penalty compared with CS found that corn residue accumulation in CC decreased soil N mineralization (Trinsoutrot et al., 2000), negatively affected soil temperature (Wilhelm and Wortmann, 2004), and contributed to the CC yield penalty (Gentry et al., 2013). Greater corn grain yield in CS than CC in this study is consistent with previous research (Varvel, 1994; West et al., 1996; Wilhelm and Wortmann, 2004; Wortmann et al., 2011; Boyer et al., 2013).

Harvest index generally followed the grain and stover trends for CS and C1 (Table 3). Our results indicated that corn in CS and C1 had about 5% greater harvest index (HI) than CC. It was also observed that CS had 15% higher HI than CC when no N was applied. Nitrogen rate increased HI and reached the maximum at 112 kg N ha^{-1} (data not shown). This was true for all rotations, with the greatest HI of 0.53 in CS while CC had a 0.48 HI at this N rate. The HI for CC in this study was similar to that reported as 0.49 across a large number of field studies conducted across range of environments (Ciampitti and Vyn, 2012). Our findings show significant HI improvements for corn rotated with soybean compared with monoculture.

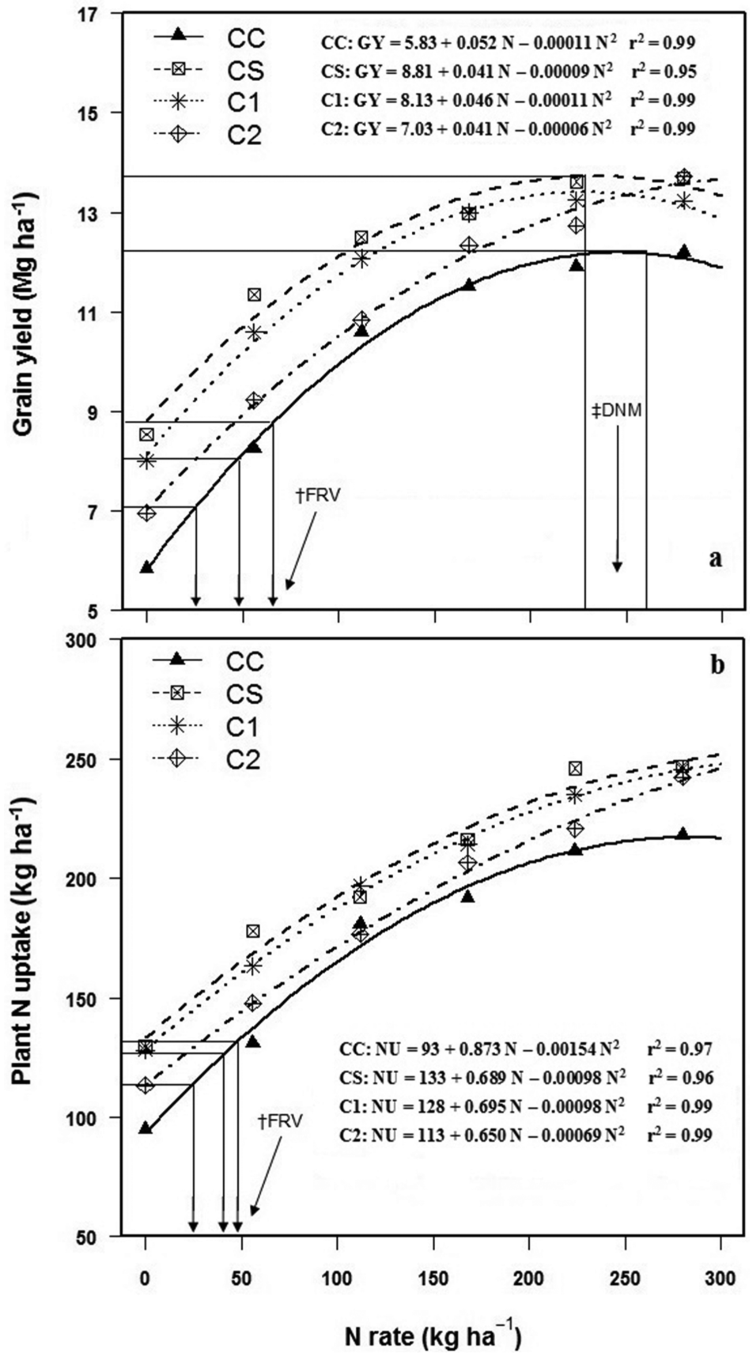

Fig. 4. (a) Grain yield and (b) plant N uptake in response to applied N rate for corn in rotation across 2006 to 2008. Regression lines are plotted by the second-order polynomial model. Analysis was conducted on the corn phase of continuous corn (CC), corn–soybean or soybean–corn (CS), and soybean–corn–corn, corn–soybean–corn, or corn–corn–soybean rotations that provided first-year corn (C1) and second-year corn (C2). †FRV, fertilizer replacement value. ‡DNM, difference in N rates at maximum yield.

Correlation between Nitrogen Indicators and Corn Grain Yield

Table 4 compares the in-season indicators; the N rate at which the variables reached a plateau are listed for comparison. SPAD reading at V10 or R2 did not account for the soybean N credit for CS and C1 because the N rate SPAD vs. yield plateaus were 170 vs. 92 kg ha^{-1} in CS and 176 vs. 136 kg N ha^{-1} in C1 (Table 4). Across rotations, the N rate SPAD at V10 or R2 vs. yield plateaus were not significantly different (Table 4). SPAD readings were significantly correlated with grain yield and had a higher correlation coefficient for CC than CS or C1. We speculate that factors related to the low soil organic matter and other beneficial rotational effects might have contributed to the discrepancy of N rate SPAD vs. yield plateaus in CS and C1.

The stalk NO_3^-–N concentration reached the excess level of 2000 mg kg^{-1} within a 10 kg N ha^{-1} range of those plateaued grain yield in all rotations except CS (Table 4). In CS, the plateau N rate of 115 kg ha^{-1} for stalk NO_3^-–N was significantly higher than the plateau N rate of 92 kg ha^{-1} for grain yield.

Table 4. Nitrogen rate at which a variable reaches a plateau value as predicted by a linear plateau regression model and Pearson's correlation (*r*) of SPAD readings at V10, SPAD readings at R2, and stalk NO_3^-–N with corn grain yield for continuous corn (CC), corn in a corn–soybean rotation (CS), and first-year corn (C1) and second-year corn (C2) in a 3-yr rotation.

	N rate				Rotation
Variable	CC	CS	C1	C2	mean
SPAD at V10†	182 ± 14‡	170 ± 19	176 ± 26	186 ± 20	178 ± 20
SPAD at R2	172 ± 12	169 ± 23	179 ± 19	175 ± 24	174 ± 20
Stalk NO_3^-–N§	165 ± 15	115 ± 9	135 ± 10	180 ± 18	149 ± 13
Grain yield	170 ± 15	92 ± 8	136 ± 10	190 ± 17	145 ± 13
Plateau yield, Mg ha^{-1}	12.0	13.2	13.1	13.1	12.9
SPAD at V10	0.65***	0.47***	0.56***	0.51***	0.73***
SPAD at R2	0.90***	0.83***	0.75***	0.84***	0.84***
Stalk NO_3^-–N	0.62***	0.58***	0.54***	0.70***	0.60***

*** Significant at the 0.001 probability level.

† Absolute maximum SPAD value across rotations at V10 and R2 were 54 and 63 SPAD readings, respectively.

‡ Mean ± standard error of the estimate.

§ Stalk NO_3^-–N was linearly increasing with no maximum. N rate was predicted by the linear model to produce 2000 mg kg^{-1}.

Across rotations, the stalk NO_3^-–N test accurately predicted the excess N rate because the plateau N rate was 149 kg ha^{-1} for stalk NO_3^-–N vs. 145 kg ha^{-1} for grain yield. Stalk NO_3^-–N was also significantly correlated with grain yield for all rotations, but higher correlation coefficients were observed for CC or C2 compared with CS or C1 (Table 4). The difference between CC and CS for how these indicators are correlated with grain yield suggests that a different procedure might be needed to interpret the values for CS in sandy loam soils.

Nitrogen Uptake and Nitrogen Harvest Index

Rotation and N rate significantly influenced corn stover, grain, and plant N uptake (Table 5). Corn–soybean and C1 produced 16 to 20% greater stover, grain, and plant N uptake compared with CC (Table 5). It is worth noting that CS increased plant N uptake by 37% compared with CC when no N was applied. Agreeing with N indicators, N uptake traits indicated that there was more N available to be taken up by corn in CS than in CC. Previous research conducted on Rozetta silt loam attributed greater N uptake by C1 to enhanced N availability through soybean root-induced N mineralization and increased biological activity (Vanotti and Bundy, 1995). Similar results were reported by Ennin and Clegg (2001), who found greater N uptake by CS than CC grown on Sharpsburg silty clay loam soils.

Of interest is whether the increased yield in CS is due to more effective partitioning of the N in the plant or just more N. In this study, rotation did not significantly affect the N harvest index (NHI) (Table 5). These results indicate that N uptake is a greater contributor than NHI to increased grain and N utilization in CS compared with CC. Previous research has documented that NHI has a minor contribution to variation in N utilization, supporting the basic assumption that NHI is more related to plant species and genotype than management or other environmental factors (Worku et al., 2007; Hernandez-Ramirez et al., 2011). The lack of a significant rotation effect on NHI agrees with the findings of Hernandez-Ramirez et al. (2011) and Wortmann et al. (2011).

Soybean Nitrogen Credit for Corn

Previous research has used several methods for estimating the soybean N credit to the following corn in a CS rotation. Of these methods, the fertilizer replacement value (FRV) (LaRue and Patterson, 1981; Ding et al., 1998; Varvel and Wilhelm, 2003) and difference in N rates at maximum yield (DNM) (Smith et al., 1987; Bundy et al., 1993; Lory et al., 1995) have been widely used. The FRV approach estimates the N credit by considering the N rate required to produce an equal yield in CC

Table 5. Nitrogen uptake traits, N harvest index (NHI), N use efficiency (NUE), and N recovery efficiency (NRE) as affected by rotation (R), N rate (N), and their interaction across 2006 to 2008.

		N uptake					
Rotation	df	Stover	Grain	Plant	NHI	NUE	NRE
		———kg ha^{-1}———				—kg kg^{-1}—	
CC†		55 b‡	115 c	171 c	0.67	16 c	0.30 c
CS		64 a	138 a	201 a	0.69	27 a	0.47 a
C1		64 a	133 ab	197 ab	0.68	24 a	0.43 ab
C2		59 ab	127 b	185 b	0.68	20 b	0.38 b
Source of variation				ANOVA			
R	3	0.022	<0.0001	0.0001	0.523	<0.0001	0.0003
N	5	<0.0001	<0.0001	<0.0001	0.0005	<0.0001	0.160
N linear	1	<0.0001	<0.0001	<0.0001	0.717	<0.0001	0.891
N quadratic	1	0.318	<0.0001	<0.0001	<0.0001	0.016	0.011
R × N	15	0.504	0.198	0.725	0.060	<0.0001	0.005
CV, %		19.8	9.9	10.8	6.1	33.0	37.4

† CC, continuous corn; CS, corn in a corn–soybean rotation; C1, first-year corn; C2, second-year corn.

‡ Least significant difference at the 95% confidence level by GLIMMIX-SAS procedure; means in each column followed by the same letter are not significantly different.

to that produced in CS when no N was applied to be the soybean N credit. The DNM approach estimates the N credit based on the differences in the N rate required to maximize yield in CC and CS. In the current study, we used the FRV and DNM approaches to determine the soybean N credit to the following corn in a CS rotation compared with CC.

A complete N balance could not be calculated in this study; however, we attempted to estimate the soybean N credit by fitting a second-order polynomial regression model on corn grain yield and plant N uptake. The relationship of grain yield and plant N uptake with N rate for each cropping system using a second-order polynomial regression are presented in Fig. 4a and Fig. 4b, respectively. The FRV approach based on the grain yield response to N rate estimated a soybean N credit for the following corn crop of 66 kg N ha^{-1} in CS, 49 kg N ha^{-1} in C1, and 26 kg N ha^{-1} in C2 (Fig. 4a). Application of the FRV approach to the plant N uptake response to N rate estimated the soybean N credit for the following corn crop in CS, C1, and C2 to be 49, 44, and 26 kg N ha^{-1}, respectively (Fig. 4b). Using the FRV approach, Varvel and Wilhelm (2003) reported a soybean N credit of 72 kg N ha^{-1} for irrigated corn grown on a Hord silt loam soil (a Haplustoll) in the Platte Valley near Shelton, NE.

The DNM approach, based on a quadratic grain yield response to N rate, estimated a soybean N credit for the following corn crop of 32 kg N ha^{-1} for CS and 30 kg N ha^{-1} for C1 (Fig. 4a) but was not applicable for C2 based on grain yield or for CS, C1, or C2 based on plant N uptake. This is because the N rate maximizing the grain yield in CC was less than in C2 and the N rate maximizing the plant N uptake in CC was less than in CS, C1, or C2 (Fig. 4).

When the approaches are combined, the average soybean N credits estimated are 49, 41, and 26 kg N ha^{-1} for the following corn crop in CS, C1, and C2, respectively. This is similar to the soybean N credit in CS derived mostly for silt loam soils used in the current Nebraska recommendation of 50 kg ha^{-1} (Shapiro et al., 2008). No research of which we are aware has reported a soybean N credit to C2. Gentry et al. (2001) reported that the soybean N credit for the following corn crop in a Typic Haplaquoll soil was a result of decreased soil N mineralization by corn residue and biological N_2 fixation.

Nitrogen Use Efficiency

Rotation, N rate, and their interaction significantly affected NUE and NRE (Table 5). Corn–soybean had the greatest NUE of 27 kg increased grain yield kg^{-1} N, which was 69% higher than the NUE of CC. Rotation × N rate interaction significantly influenced NUE, which exhibited a quadratic convex for CS and a quadratic concave for other rotations (Fig. 5). Corn–soybean and C1 produced greater NUEs of 38 and 30 kg increased grain yield kg^{-1} N, respectively, at 50 kg fertilizer N ha^{-1} (Fig. 5). At this N rate, CC and C2 produced much lower NUEs of 9 and 19 kg increased grain yield kg^{-1} N, respectively (Fig. 5). Continuous corn and C2 required 130 kg more N ha^{-1} to maximize the NUE to 20 and 22 kg increased

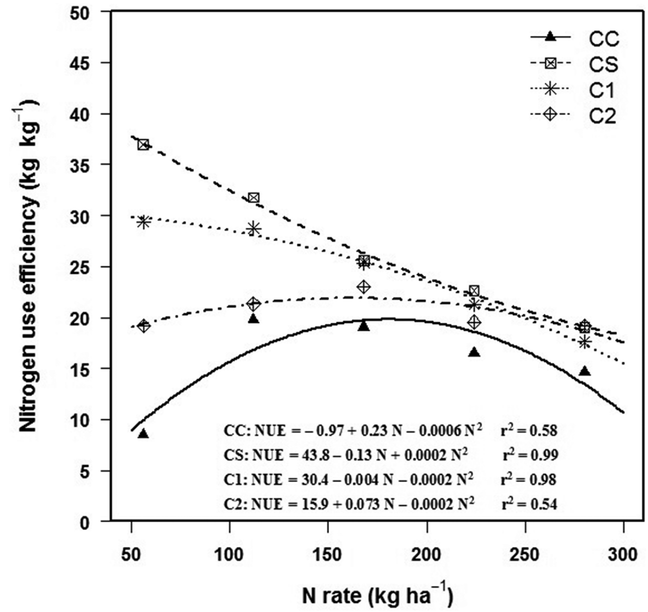

Fig. 5. Corn N use efficiency (kg increased grain yield kg^{-1} fertilizer and irrigation water N) as affected by rotation × N rate interaction during 2006 to 2008. Regression lines are plotted by the second-order polynomial model. Analysis was conducted on the corn phase of continuous corn (CC), corn–soybean or soybean–corn (CS), and soybean–corn–corn, corn–soybean–corn, or corn–corn–soybean rotations that provided first-year corn (C1) and second-year corn (C2).

grain yield kg^{-1} N, respectively (Fig. 5). Pikul et al. (2005) defined NUE by including soil mineral N and reported 22% greater corn NUE in CS than CC grown on Barnes sandy clay loam soil (a frigid Calcic Hapludoll). Nitrogen use efficiency in the present study is similar to that reported by Wortmann et al. (2011): 30 kg increased grain yield kg^{-1} N for irrigated corn rotated with soybean in Nebraska.

The NRE was significantly influenced by both rotation and rotation × N rate interaction (Table 5). Corn–soybean followed by C1 had, on average, 55% higher NRE than CC (Table 5). A similar trend for NUE in response to an N rate × rotation interaction was observed for NRE. A greater NRE of corn in CS compared with CC agrees with previous research findings (Varvel and Peterson, 1990; Wortmann et al., 2011). Wortmann et al. (2011) reported 12% higher NRE in CS than CC across large-scale field studies in Nebraska. The mean NRE for CS and C1 in the sandy soil of this study is similar to that reported by Ciampitti and Vyn (2012), 0.46 kg increased plant N uptake kg^{-1} N, for a large number of corn trials from 1940 to 2011. Therefore, improved NUE and NRE for irrigated corn in sandy soil is possible by growing corn with soybean in 2- to 3-yr rotations.

CONCLUSIONS

Our findings indicate that planting corn with soybean in 2- to 3-yr rotations on sandy loam soils of north-central Nebraska can improve corn N use and recovery efficiencies for greater yields with less N inputs. Soybean seed yield did not respond to fertilizer N, but at this site there was an average 55 kg N ha^{-1} yr^{-1} of irrigation water N, which may have contributed to the soybean being nonresponsive. Rotation did not affect soybean yields; even the continuous soybean maintained yield, although the practice is not recommended.

Crop N indicators, SPAD readings at V10 and R2 and stalk NO_3^-–N data, showed that more N was available for corn in CS or C1 than CC. Results indicated that the 0.95 critical SPAD level used for silt loam soils is appropriate for sandy loam. The threshold of 2000 mg kg^{-1} stalk NO_3^-–N concentration was applicable for CC, but a lower value might be needed for CS in sandy loam. Corn–soybean resulted in a 20% grain yield increase and an 11% stover production increase compared with CC. The more available N in CS and C1 than in CC is attributed to a soybean N credit that may be a combination of reduced N immobilization and increased biological activity. The CS rotation produced 8% greater plant N uptake than that obtained from CC and significantly improved N use and N recovery efficiencies. The average estimated soybean N credits for the following corn crop in CS, C1, and C2 were 49, 41, and 26 kg N ha^{-1}, respectively. The C1 and C2 corn tended to be intermediate in all indicators compared with CC and CS. These results show that careful consideration of the soybean N contribution when making N recommendations, even on low-organic-matter sandy soils, will result in significant improvements in N uptake and N use efficiencies for the following corn crop.

ACKNOWLEDGMENTS

Partial funding for this research was provided by the Upper Elkhorn Natural Resources District. We would like to thank Crop Consultant Mr. Mark Pavlik and Research Technologist Dr. Jon Scott for their help with field activities. Appreciation is extended to the Zuhlke family of Brunswick, NE, for use of their land.

REFERENCES

Angle, J.S. 1990. Nitrate leaching losses from soybean (*Glycine max* L. Merr.). Agric. Ecosyst. Environ. 31:91–97. doi:10.1016/0167-8809(90)90212-V

Binford, G.D., A.M. Blackmer, and N.M. El-Hout. 1990. Tissue test for excess nitrogen during corn production. Agron. J. 82:124–129. doi:10.2134/agronj1990.00021962008200010027x

Blackmer, A.M., and A.P. Mallarino. 1996. Corn stalk testing to evaluate nitrogen management. PM-1584. Iowa State Univ. Ext., Ames. http://www.extension.iastate.edu/Publications/PM1584.pdf (accessed 7 Jan. 2013).

Blevins, R.L., J.H. Herbek, and W.W. Frye. 1990. Legume cover crops as a nitrogen source for no-till corn and grain sorghum. Agron. J. 82:769–772. doi:10.2134/agronj1990.00021962008200040023x

Boyer, C.N., J.A. Larson, R.K. Roberts, A.T. McClure, D.D. Tyler, and V. Zhou. 2013. Stochastic corn yield response functions to nitrogen for corn after corn, corn after cotton, and corn after soybean. J. Agric. Appl. Econ. 45:669–681.

Boyer, C.N., R.K. Roberts, J.A. Larson, M.A. McClure, and D.D. Tyler. 2015. Risk effects on optimal nitrogen rates for corn rotations in Tennessee. Agron. J. 107:896–902. doi:10.2134/agronj14.0546

Bremner, J.M. 1996. Nitrogen—Total. In: D.L. Sparks et al., editors, Methods of soil analysis. Part 3. Chemical methods. SSSA Book Ser. 5. SSSA and ASA, Madison, WI. p. 1085–1089.doi:10.2136/sssabookser5.3.c37

Bundy, L.G., T.W. Andraski, and R.P. Wolkowski. 1993. Nitrogen credits in soybean–corn sequences on three soils. Agron. J. 85:1061–1067. doi:10.2134/agronj1993.00021962008500050020x

Carmer, S.G., W.E. Nyquist, and W.M. Walker. 1989. Least significant differences for combined analyses of experiments with two- or three-factor treatment designs. Agron. J. 81:665–672. doi:10.2134/agronj1989.00021962008100040021x

Cassman, K.G., A. Dobermann, and D.T. Walters. 2002. Agroecosystems, nitrogen use efficiency, and nitrogen management. Ambio 31:132–140. doi:10.1579/0044-7447-31.2.132

Cate, R.B., and L.A. Nelson. 1971. A simple statistical procedure for partitioning soil test correlation data into two classes. Soil Sci. Soc. Am. J. 35:658–660. doi:10.2136/sssaj1971.03615995003500040048x

Ciampitti, I.A., and T.J. Vyn. 2012. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. Field Crops Res. 133:48–67. doi:10.1016/j.fcr.2012.03.008

Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83:108–113. doi:10.2134/agronj1991.00021962008300010026x

Ding, W., D.J. Hume, T.J. Vyn, and E.G. Beauchamp. 1998. Nitrogen credit of soybean to a following corn crop in central Ontario. Can. J. Plant Sci. 78:29–34. doi:10.4141/P96-180

Ennin, S.A., and M.D. Clegg. 2001. Effect of soybean plant population in a soybean and maize rotation. Agron. J. 93:396–403. doi:10.2134/agronj2001.932396x

Foltz, J.C., J.G. Lee, M.A. Martin, and P.V. Preckel. 1995. Multiattribute assessment of alternative cropping systems. Am. J. Agric. Econ. 77:408–420. doi:10.2307/1243550

Forrestal, P.J., R.J. Kratochvil, and J.J. Meisinger. 2012. Late-season corn measurement to assess soil nitrate and nitrogen management. Agron. J. 104:148–157. doi:10.2134/agronj2011.0172

Fox, R.H., W.P. Piekielek, and K.E. Macneal. 2001. Comparison of late-season diagnostic tests for predicting nitrogen status of corn. Agron. J. 93:590–597. doi:10.2134/agronj2001.933590x

Gentry, L.E., F.E. Below, M.B. David, and J.A. Bergerou. 2001. Source of the soybean N credit in maize production. Plant Soil 236:175–184. doi:10.1023/A:1012707617126

Gentry, L.F., M.L. Ruffo, and F.E. Below. 2013. Identifying factors controlling the continuous corn yield penalty. Agron. J. 105:295–303. doi:10.2134/agronj2012.0246

Halvorson, A.D., and C.A. Reule. 2006. Irrigated corn and soybean response to nitrogen under no-till in northern Colorado. Agron. J. 98:1367–1374. doi:10.2134/agronj2006.0065

Hassink, J. 1994. Effects of soil texture and grassland management on soil organic C and N and rates of C and N mineralization. Soil Biol. Biochem. 26:1221–1231. doi:10.1016/0038-0717(94)90147-3

Hernandez-Ramirez, G., S.M. Brouder, D.R. Smith, and G.E. Van Scoyoc. 2011. Nitrogen partitioning and utilization in corn cropping systems: Rotation, N source, and N timing. Eur. J. Agron. 34:190–195. doi:10.1016/j.eja.2010.12.002

Hesterman, O.B., C.C. Sheaffer, D.K. Barnes, W.E. Lueshen, and J.H. Ford. 1986. Alfalfa dry matter and nitrogen production, and fertilizer nitrogen response in legume–corn rotations. Agron. J. 78:19–23. doi:10.2134/agronj1986.00021962007800010005x

Huang, W.-Y., D. Shank, and T.I. Hewitt. 1996. On-farm costs of reducing residual nitrogen on cropland vulnerable to nitrate leaching. Appl. Econ. Perspect. Policy 18:325–339. doi:10.2307/1349619

Huggins, D.R., and W.L. Pan. 2003. Key indicators for assessing nitrogen use efficiency in cereal-based agroecosystems. J. Crop Prod. 8:157–185. doi:10.1300/J144v08n01_07

Jawson, M.D., A.J. Franzluebbers, D.K. Galusha, and R.M. Aiken. 1993. Soil fumigation within monoculture and rotation: Response of corn and mycorrhizae. Agron. J. 85:1174–1180. doi:10.2134/agronj1993.00021962008500060016x

Katupitiya, A., D.E. Eisenhauer, R.B. Ferguson, R.F. Spalding, F.W. Roeth, and M.W. Bobier. 1997. Long-term tillage and crop rotation effects on residual nitrate in the crop root zone and nitrate accumulation in the intermediate vadose zone. Trans. ASAE 40:1321–1327. doi:10.13031/2013.21390

LaRue, T.A., and T.G. Patterson. 1981. How much nitrogen do legumes fix? Adv. Agron. 34:15–38. doi:10.1016/S0065-2113(08)60883-4

Lord, E.I., and R.D.J. Mitchell. 1998. Effects of nitrogen inputs to cereals on nitrate leaching from sandy soils. Soil Use Manage. 14:78–83. doi:10.1111/j.1475-2743.1998.tb00619.x

Lory, J.A., M.P. Russelle, and T.A. Peterson. 1995. A comparison of two nitrogen credit methods: Traditional vs. difference. Agron. J. 87:648–651. doi:10.2134/agronj1995.00021962008700040007x

Mohammed, M.S., and M.D. Clegg. 1993. Pearl millet–soybean rotation and

nitrogen fertilizer effects on millet productivity. Agron. J. 72:613–616.
National Agricultural Statistics Service. 2014. 2014 state agriculture overview: Nebraska. NASS, Washington, DC. http://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=NEBRASKA (accessed 17 July 2015).
National Agricultural Statistics Service. 2015. Crop production: 2014 summary. NASS, Washington, DC. http://usda.mannlib.cornell.edu/usda/current/CropProdSu/CropProdSu-01-12-2015_revision.pdf (accessed 17 July 2015).
Parker, M.B., and H.B. Harris. 1977. Yield and leaf nitrogen of nodulating and non-nodulating soybeans as affected by nitrogen and molybdenum. Agron. J. 69:551–554. doi:10.2134/agronj1977.00021962006900040007x
Peoples, M.B., and D.F. Herridge. 1990. Nitrogen fixation by legumes in tropical and subtropical agriculture. Adv. Agron. 44:155–223. doi:10.1016/S0065-2113(08)60822-6
Peterson, T.A., and G.E. Varvel. 1989. Crop yield as affected by rotation and nitrogen rate: III. Corn. Agron. J. 81:735–738. doi:10.2134/agronj1989.00021962008100050007x
Piekielek, W.P., R.H. Fox, J.D. Coth, and K.E. Macneal. 1995. Use of a chlorophyll meter at the early dent stage of corn to evaluate nitrogen sufficiency. Agron. J. 87:403–408. doi:10.2134/agronj1995.00021962008700030003x
Pikul, J.L., Jr., L. Hammack, and W.E. Riedell. 2005. Corn yield, nitrogen use, and corn rootworm infestation of rotations in the northern Corn Belt. Agron. J. 97:854–863. doi:10.2134/agronj2004.0263
Purcell, L.C., R. Serraj, T.R. Sinclair, and A. De. 2004. Soybean N_2 fixation estimates, ureide concentration, and yield responses to drought. Crop Sci. 44:484–492. doi:10.2135/cropsci2004.4840
Raimbault, B.A., and T.J. Vyn. 1991. Crop rotation and tillage effects on corn growth and soil structural stability. Agron. J. 83:979–985. doi:10.2134/agronj1991.00021962008300060011x
Riedell, W.E., T.E. Schumacher, S.A. Clay, M.M. Ellsbury, M. Pravecek, and P.D. Evenson. 1998. Corn and soil fertility response to crop rotation with low, medium, or high inputs. Crop Sci. 38:427–433. doi:10.2135/cropsci1998.0011183X003800020026x
Ritchie, S.W., J.J. Hanway, G.O. Benson, J.C. Herman, and S.J. Lupkes. 1993. How a corn plant develops. Spec. Rep. 48. Iowa State Univ. Coop. Ext. Serv., Ames.
Ritz, C., and J. Strebig. 2010. Analysis of dose–response curves. R Found. Stat. Comput., Vienna. http://cran.r-project.org/web/packages/drc/drc.pdf (accessed 10 Dec. 2012).
Salvagiotti, F., J.E. Specht, K.G. Cassman, D.T. Walters, A. Weiss, and A. Dobermann. 2009. Growth and nitrogen fixation in high-yielding soybean: Impact of nitrogen fertilization. Agron. J. 101:958–970. doi:10.2134/agronj2008.0173x
Schmitt, M.A., J.A. Lamb, G.W. Randall, J.H. Orf, and G.W. Rehm. 2001. In-season fertilizer nitrogen applications for soybean in Minnesota. Agron. J. 93:983–988. doi:10.2134/agronj2001.935983x
Shapiro, C.A., R.B. Ferguson, G.W. Hergert, C.S. Wortmann, and D.T. Walters. 2008. Fertilizer suggestions for corn. Ext. Publ. EC117. Univ. of Nebraska Coop. Ext., Lincoln. http://extensionpublications.unl.edu/assets/pdf/ec117.pdf (accessed 13 Jan. 2014).
Shapiro, C.A., D.D. Francis, R.B. Ferguson, G.W. Hergert, T.M. Shaver, and C.S. Wortmann. 2006. Using a chlorophyll meter to improve N management. Ext. Publ. G1632. Univ. of Nebraska Coop. Ext., Lincoln. http://extensionpublications.unl.edu/assets/pdf/g1632.pdf (accessed 13 Jan. 2014).
Sindelar, A.J., J.A. Coulter, J.A. Lamb, and J.A. Vetsch. 2015. Nitrogen, stover, and tillage management affect nitrogen use efficiency in continuous corn. Agron. J. 107:843–850. doi:10.2134/agronj14.0535
Smith, M.S., W.W. Frye, and J.J. Varco. 1987. Legume winter cover crops. Adv. Soil Sci. 7:95–139. doi:10.1007/978-1-4612-4790-6_3
Soares Novo, M.C., R.T. Tanaka, H.A.A. Mascarenhas, N. Bortoletto, P.B. Gallo, J.C.V.N. Alves Pereira, and A.A. Teixeira. 1999. Nitrogen and potassium in nitrogen symbiotic fixation of winter soybean. Sci. Agric. 56:143–156.
Soil Conservation Service. 1983. Soil survey of Holt County, Nebraska. US Gov. Print. Serv., Washington, DC. http://www.nrcs.usda.gov/Internet/FSE_MANUSCRIPTS/nebraska/NE089/0/holt.pdf (accessed 30 July 2015).
Stanger, T.F., and J.G. Lauer. 2008. Corn grain yield response to crop rotation and nitrogen over 35 years. Agron. J. 100:643–650. doi:10.2134/agronj2007.0280
Trinsoutrot, I., S. Recous, B. Bentz, M. Linères, D. Chèneby, and B. Nicolardot. 2000. Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. Soil Sci. Soc. Am. J. 64:918–926. doi:10.2136/sssaj2000.643918x
Vanotti, M.B., and L.G. Bundy. 1995. Soybean effects on soil nitrogen availability in crop rotations. Agron. J. 87:676–680. doi:10.2134/agronj1995.00021962008700040012x
Varvel, G.E. 1994. Rotation and nitrogen fertilization effects on changes in soil carbon and nitrogen. Agron. J. 86:319–325. doi:10.2134/agronj1994.00021962008600020021x
Varvel, G.E., and T.A. Peterson. 1990. Nitrogen fertilizer recovery by corn in monoculture and rotation systems. Agron. J. 82:935–938. doi:10.2134/agronj1990.00021962008200050019x
Varvel, G.E., and T.A. Peterson. 1992. Nitrogen fertilizer recovery by soybean in monoculture and rotation systems. Agron. J. 84:215–218. doi:10.2134/agronj1992.00021962008400020018x
Varvel, G.E., J.S. Schepers, and D.D. Francis. 1997a. Ability for in-season correction of nitrogen deficiency in corn using chlorophyll meters. Soil Sci. Soc. Am. J. 61:1233–1239. doi:10.2136/sssaj1997.03615995006100040032x
Varvel, G.E., J.S. Schepers, and D.D. Francis. 1997b. Chlorophyll meter and stalk nitrate techniques as complementary indices for residual nitrogen. J. Prod. Agric. 10:147–151. doi:10.2134/jpa1997.0147
Varvel, G.E., and W.W. Wilhelm. 2003. Soybean nitrogen contribution to corn and sorghum in western Corn Belt rotations. Agron. J. 95:1220–1225. doi:10.2134/agronj2003.1220
West, T.D., D.R. Griffith, G.C. Steinhardt, E.J. Kladivko, and S.D. Parsons. 1996. Effect of tillage and rotation on agronomic performance of corn and soybean: Twenty-year study on dark silty clay loam soil. J. Prod. Agric. 9:241–248. doi:10.2134/jpa1996.0241
Wilhelm, W.W., and C.S. Wortmann. 2004. Tillage and rotation interactions for corn and soybean grain yield as affected by precipitation and air temperature. Agron. J. 96:425–432. doi:10.2134/agronj2004.0425
Worku, M., M. Bänziger, G.S. Erley, D. Friesen, A.O. Diallo, and W.J. Horst. 2007. Nitrogen uptake and utilization in contrasting nitrogen efficient tropical maize hybrids. Crop Sci. 47:519–528. doi:10.2135/cropsci2005.05.0070
Wortmann, C.S., D.D. Tarkalson, C.A. Shapiro, A.R. Dobermann, R.B. Ferguson, G.W. Hergert, and D. Walters. 2011. Nitrogen use efficiency of irrigated corn for three cropping system in Nebraska. Agron. J. 103:76–84. doi:10.2134/agronj2010.0189